

**NEW MATHEMATICAL MODELS OF
BIOMASS VIABILITY AND MEMBRANE
FOULING IN A MEMBRANE BIOREACTOR**

By

Mst Farzana Rahman Zuthi



**Submitted in fulfilment for the degree of
Doctor of Philosophy**

Faculty of Engineering and Information Technology

University of Technology, Sydney

Australia

June 2014

CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Signature of Student: 

Date: 30/06/2014

Acknowledgements

I would like to take this opportunity to express my sincere thanks and deep gratitude to my honorable supervisors who have provided continuous and unlimited supports throughout my PhD research. It would not be possible for me to complete this dissertation without their valuable suggestions and timely guidance during the course of my study. My deepest admiration goes to my principal supervisor Professor Huu Hao Ngo for many fruitful discussions to share his vast research experience and wisdom relevant to my research. Professor Ngo directed me towards the correct path with great patience and understanding about my abilities and limitations. He has always engaged me in various research activities, and hence, has encouraged me to expand my ideas and thoughts. I wish to express my gratitude and many thanks to my alternate supervisor, Dr. Wenshan Guo, for all her unforgettable assistance throughout my research journey especially for her support to perform the experimental work in a systematic and efficient way.

I would like to thank the Australian Government and the UTS authority for awarding me The Australian Postgraduate Award for doctoral study which was a great support for my research. I would also like to thank the MBR research funding from Prof. Ngo's project that supported the expenses of my research and provided a timely financial support for me when I finished getting the APA scholarship payment.

I also wish to express my thanks to the academic administrative staff of FEIT and the Graduate Research School, technical staff and supervisors of the Environmental Engineering Laboratory of the UTS who have always been remarkably supportive to me. I want to especially thank Md. Johir for his assistance in the experimental research. Special thanks go to Ms Lijuan and Ms Chau who were always been helpful during the

experimental set-up processes and operation. My earnest thanks are to all the fellow researchers of our sustainable water research group who shared their research experience and thoughts which greatly inspired me to do a better PhD research.

My acknowledgement will never be completed without thanking my family and friends; especially my husband, my son, my parents and parent-in-laws. My husband Maruful Hasan has always inspired me to hold positive thinking towards research activities, and my son Zarif Hasan has also been considerate about my engagement in the research work. I would also like to thank my siblings for their never ending love and supports. Above all, I would like express my true faith and gratitude to ALMIGHTY who gave me the opportunity to bring this research to an end through a life path with many ups and downs.

Abstract

The optimized performance of a membrane bioreactor (MBR) for wastewater treatment depends not only on the biomass viability but also on the dynamic effects of biomass properties on membrane fouling. This research developed new conceptual mathematical models of biomass viability and fouling using biomass parameters and operational parameters of an MBR. It also presents, as outcomes, new simple and practical models for tracking biomass viability and fouling of an MBR system. The proposed models can be used to track instability in the operation of an MBR, and consequently, measures can be taken to act against instability in the oxygen uptake and for fouling control.

The proposed conceptual models include parameters such as the specific oxygen uptake rate (SOUR) of microorganisms, the soluble or colloidal chemical oxygen demand (COD) of effluent along with the mixed liquor suspended solids (MLSS) and mixed liquor volatile suspended solids (MLVSS) concentrations. The COD parameters of the models represent soluble microbial product (SMP) or bound extra-polymeric substances (bEPS) present within an MBR, offering the possibility of developing practical models with these easily measurable parameters.

The experimental study investigated the effects of biomass parameters on SOUR in a lab-scale sponge submerged MBR (SSMBR) system. Statistical analyses of experimental results indicate that bEPS, SMP, MLSS and MLVSS had significant effects on SOUR and their relative influence on SOUR was $\text{EPS} > \text{bEPS} > \text{SMP} > \text{MLVSS/MLSS}$. The EPS is considered as a lumped parameter of SMP and bEPS. The progressive change of SMP and bEPS within the bioreactor consistently maintained a negative exponential correlation with SOUR, and two independent models of biomass viability were developed based on

correlations among these parameters. Both the model simulations for biomass viability agreed well with experimental values of the SSMBR system.

The simplified model of membrane fouling considered cake formation on the membrane and its pore blocking as the major processes of fouling. In the model, MLSS is used as a lumped parameter to describe the cake layer formation including the biofilm whereas SMP is assumed as the key contributor to pore fouling. The combined effects of aeration and backwash on detachment of membrane foulants, and new exponential coefficients are included to better describe the exponential increase of transmembrane pressure (TMP). With practical assumptions of these major processes, the new model successfully simulated the fouling phenomena with fairly accurate predictions of the rise of TMP for the operations of two lab-scale submerged MBR systems.

List of Publications

(06 journal papers published, 02 journal papers submitted, 03 conference presentation)

Journal Publications:

1. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Chen, S.S., Nguyen N. C., Deng, L. J., Tran, T. D.C. (2014). An Assessment of the Effects of Microbial Products on the Specific Oxygen Uptake in Submerged Membrane Bioreactor. International Journal of Environmental, Earth Science and Engineering 8(2) 22-26.
2. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S. (2013). New proposed conceptual mathematical models for biomass viability and membrane fouling of membrane bioreactor. Bioresource Technology 142, 137-40.
3. **Zuthi, M. F. R.,** Guo, W. S., Ngo, H. H., Nghiem, L., Hai, F. I. (2013). Enhanced Biological Phosphorus Removal and its Modeling for the Activated Sludge and Membrane Bioreactor Processes. Bioresource Technology **139, 363-74.**
4. **Zuthi, M.F.R.,** Ngo, H. H., Guo, W. S., Zhang, J., Liang, S. (2013). A review towards finding a simplified approach for modelling the kinetics of the soluble microbial products (SMP) in an integrated mathematical model of membrane bioreactor (MBR). International Biodeterioration and Biodegradation 85, 466-473.
5. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nguyen, T.T. (2013). The effects of sponges on the dissolved organic removal in a sponge submerged membrane bioreactor. World Academy of Science and Technology (WASET) 78, 44-48.
6. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S. 2012. Modelling bioprocesses and membrane fouling in membrane bioreactor (MBR): a review towards finding an integrated model framework. Bioresource Technology 122, 119-29.

7. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nghiem, D. L., Hai, F. I. , Xia, S. Q., Zhang, Z. Q., Li, J. X. Biomass viability: identification of influencing factors and mathematical modelling in a membrane bioreactor. (Submitted to Journal of Membrane Science).
8. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nghiem, D. L., Hai, F. I., Xia, S. Q., Zhang, Z. Q., Chen, S. S., Nguyen, C. N. New and practical mathematical model of membrane fouling in an aerobic submerged membrane bioreactor (Submitted to Water Research).

Conference Presentation:

1. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Chen, S.S., Nguyen N. C., Deng, L. J., Tran, T. D.C. (2014). An Assessment of the Effects of Microbial Products on the Specific Oxygen Uptake in Submerged Membrane Bioreactor. ICEBESE 2014: International Conference on Environmental, Biological and Ecological Sciences, and Engineering, 13-14 February, 2014, Kualalumpur, Malaysia.
2. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., Nguyen, T.T. 2013. The effects of sponges on the dissolved organic removal in a sponge submerged membrane bioreactor. ICEBESE 2013: International Conference on Environmental, Biological and Ecological Sciences, and Engineering, 5-6 June, 2013, New York, USA.
3. **Zuthi, M. F. R.,** Ngo, H. H., Guo, W. S., 2012. A simplified approach for modelling the formation and degradation of soluble microbial products (SMP) in an integrated mathematical model of MBR. CESE 2012: the fifth annual conference on the challenges in environmental science and engineering, 9-13 September, 2012, Melbourne, Australia.

Table of Contents

	Page
Certificate of Original Authorship	ii
Acknowledgements	iii
Abstract	v
List of Publications.....	vii
Table of Contents	ix
List of Tables	xiii
List of Figures	xiv
List of Notations and Abbreviations	xvi
CHAPTER 1	
Introduction	
1.1 Background	1-1
1.2 Motivations and objectives of this study	1-5
1.3 Organization and major contents of the thesis	1-6
CHAPTER 2	
Literature Review	
2.1 Introduction	2-1
2.2 Membrane bioreactor for wastewater treatment	2-2
2.2.1 <i>Membrane processes and applications</i>	2-2
2.2.2 <i>MBR definitions, advantages and history of MBR development</i>	2-3
2.2.3 <i>Classification and configurations of MBRs</i>	2-5
2.2.4 <i>MBR performance and operating factors</i>	2-7
2.2.5 <i>Membrane fouling in MBRs</i>	2-13
2.2.6 <i>Correlation between biological process variables and fouling in the MBR</i> ...	2-25
2.3 A brief review on mathematical modelling of the MBR.....	2-30
2.3.1 <i>Models of biomass kinetics of the activated sludge process</i>	2-31
2.3.2 <i>Membrane fouling models</i>	2-52
2.3.3 <i>Integrated and hybrid MBR models</i>	2-60
2.4 Concluding remarks	2-66

CHAPTER 3	Page
New Conceptual Mathematical Models for Biomass Viability and Membrane Fouling of a Membrane Bioreactor	
3.1 Introduction.....	3-1
3.2 Methods of the development of conceptual models.....	3-1
3.2.1 <i>Background and state-of-the-art</i>	3-1
3.2.2 <i>New conceptual model of biomass viability</i>	3-6
3.2.3 <i>Conceptual mathematical model of membrane fouling</i>	3-8
3.3 Conclusion.....	3-10
CHAPTER 4	
Experimental Investigations	
4.1 Introduction.....	4-1
4.2 Materials and methods	4-1
4.2.1 <i>Experimental set-up</i>	4-1
4.2.2 <i>Compositions of the substrate and sponge specifications</i>	4-4
4.2.3 <i>Analysis</i>	4-5
CHAPTER 5	
Performance Evaluation of the Submerged Membrane Bioreactors for Wastewater Treatment	
5.1 Introduction.....	5-1
5.2 Evaluation of the performance of the SSMBR.....	5-2
5.2.1 <i>DOC removal efficiency of the SSMBR system</i>	5-4
5.2.2 <i>Effects of biomass on the DOC removal</i>	5-7
5.2.3 <i>Mathematical functions for the effects of biomass on the DOC removal</i>	5-9
5.3 Assessment of biomass viability in SMBR.....	5-11
5.3.1 <i>Relationships between specific oxygen uptake rate and mixed liquor properties</i>	5-13
5.3.2 <i>Relationships between specific oxygen uptake rate and SMP indicator parameter</i>	5-13
5.4 Further discussions and future perspectives	5-16

CHAPTER 6	Page
Identification of the Factors of Biomass Viability and its Mathematical Modelling for Membrane Bioreactor	
6.1 Introduction.....	6-1
6.2 Materials and methods.....	6-2
6.2.1 <i>Experimental set-up and operational parameters</i>	6-2
6.2.2 <i>Methods of analysis of biological parameters</i>	6-2
6.2.3 <i>Statistical analysis</i>	6-3
6.2.4 <i>Parameter estimation</i>	6-4
6.3 Results and discussion.....	6-4
6.3.1 <i>MLSS and SOUR profile with operation time</i>	6-4
6.3.2 <i>Correlation among biomass parameters and SOUR</i>	6-5
6.3.3 <i>SOUR profile with the progressive change of microbial products</i>	6-7
6.4 Mathematical modelling of biomass viability and validation of the model...	6-8
6.5 Conclusion.....	6-12
CHAPTER 7	
New and Practical Mathematical Model of Membrane Fouling in an Aerobic Submerged Membrane Bioreactor	
7.1 Introduction.....	7-1
7.2 Methods of measurement of fouling resistances and analysis procedure.....	7-2
7.2.1 <i>Measurements of fouling resistances</i>	7-2
7.2.2 <i>Estimation of parameters of the mathematical model</i>	7-3
7.3 Model development.....	7-3
7.3.1 <i>Resistance due to pore blocking</i>	7-3
7.3.2 <i>Resistance due to cake layer formation</i>	7-5
7.4 Results and discussion.....	7-7
7.4.1 <i>Variation of MLSS and SMP with operation time</i>	7-7
7.4.2 <i>Model analysis and application</i>	7-9
7.5 Conclusion.....	7-18

CHAPTER 8	Page
Conclusions and Recommendations	
8.1 Summary of the major findings of the research.....	8-1
8.2 Future perspectives	8-4
References	R-1
Appendix 1	A-1
Appendix 2	A-5

List of Tables

	Page
<i>Table 2.1</i> Recent findings of the effects of MBR operating conditions on membrane fouling	2-17
<i>Table 2.2</i> Mathematical expressions of some fouling indices for low pressure MBR systems	2-19
<i>Table 2.3</i> Fractions of MLSS and their relationship with membrane fouling	2-29
<i>Table 2.4</i> Fractions of microbial products and their effects on membrane fouling ...	2-30
<i>Table 2.5</i> Comparison of ASM models with regard to the simulation of MBR bioprocesses	2-34
<i>Table 2.6</i> Biokinetics of formation and degradation of SMPs.....	2-40
<i>Table 2.7</i> Comparison of different mathematical models for bio-P-removal	2-45
<i>Table 3.1</i> Studies on the effect of microbial products on microbial activity	3-5
<i>Table 4.1</i> Design parameters, operating conditions and system performance of the SSMBR	4-2
<i>Table 4.2</i> Compositions of the substrate used for the SSMBR	4-5
<i>Table 5.1</i> System descriptions and operating conditions of the SMBR systems	5-2
<i>Table 5.2</i> Dissolved Organic Carbon (DOC) concentrations in the influent and effluent at different MLSS concentrations in the SSMBR system.....	5-4
<i>Table 5.3</i> Mathematical functions for the effects of different biomass parameters on the DOC removal	5-10
<i>Table 6.1</i> Pearson- r_p correlation matrix of the biomass parameters to SOUR	6-6
<i>Table 7.1</i> Parameters and model simulation results with various porosities of membrane	7-13
<i>Table 7.2</i> Calibrated model parameters and coefficients used in simulations	7-14

List of Figures

	Page
<i>Figure 1.1</i> Research approach of the study	1-8
<i>Figure 2.1</i> Three types of MBR processes: (a) Biomass separation MBRs (b) membrane aeration bioreactors (c) Extraction MBRs	2-6
<i>Figure 2.2</i> Configuration of side stream and submerged MBRs	2-6
<i>Figure 2.3</i> Inter-relationships between MBR parameters and fouling process variables	2-12
<i>Figure 2.4</i> Classification of membrane fouling	2-14
<i>Figure 2.5</i> Illustration of membrane fouling process in MBRs (a) pore blocking (b) cake layer	2-15
<i>Figure 2.6</i> Biological parameters and process variables of ASMs	2-35
<i>Figure 2.7</i> Different concepts of the formation and degradation of SMPs used in typical modelling studies	2-39
<i>Figure 2.8</i> Schematic of the (a) ASM1-SMP hybrid model (b) ASM1-SMP-EPS hybrid model	2-43
<i>Figure 2.9</i> Flow diagram of anaerobic storage and aerobic growth of PAOs in ASM2 and ASM3-bio-P model	2-47
<i>Figure 2.10</i> Blackbox model for continuous aerobic MBR process	2-50
<i>Figure 2.11</i> Conceptual diagram of integrated model framework for MBR system	2-66
<i>Figure 4.1</i> Schematic diagram of the SSMBR experimental system	4-3
<i>Figure 4.2</i> The SSMBR experimental system	4-3
<i>Figure 4.3</i> The membrane module used for the SSMBR	4-4
<i>Figure 4.4</i> YSI 5300 biological oxygen monitor	4-6
<i>Figure 4.5</i> Ultrasonic water bath used for the EPS extraction	4-7
<i>Figure 4.6</i> Spectroquant [®] Cell photometer (NOVA 60- Merck)	4-8
<i>Figure 4.7</i> TMP versus flux plot	4-9
<i>Figure 5.1</i> DOC removal efficiency (%) of SSMBR @ initial MLSS _{sludge} \approx 10 g/L ...	5-5
<i>Figure 5.2</i> DOC removal efficiency (%) of SSMBR @ initial MLSS _{sludge} \approx 15 g/L...	5-5

	Page
<i>Figure 5.3</i> DOC removal at various $(MLSS/MLVSS)_{\text{sponge}}/MLSS_{\text{sludge}}$ (for the acclimatized sponge and initial $MLSS_{\text{sludge}} \approx 10 \text{ g/L}$)	5-7
<i>Figure 5.4</i> DOC removal vs. $(MLSS/MLVSS)_{\text{sponge}}/MLSS_{\text{sludge}}$ (for the acclimatized sponge and initial $MLSS_{\text{sludge}}$ of 15 g/L)	5-8
<i>Figure 5.5</i> Effects of different biomass parameters on DOC removal: (a) $MLSS_{\text{sponge}}$ and (b) $MLVSS_{\text{sponge}}$ (normalized to $MLSS_{\text{sludge}} \approx 10 \text{ g/L}$) (c) biomass of sponge (d) $MLSS$ concentration of the sludge	5-11
<i>Figure 5.6</i> Relationships of SOUR with $MLVSS$ and $MLVSS/MLSS$	5-13
<i>Figure 5.7</i> Relationship of SOUR with $COD_{s,eff}$	5-14
<i>Figure 5.8</i> Relationships of SMP with SOUR and $COD_{s,eff}$	5-15
<i>Figure 6.1</i> Variation of $MLSS$ and SOUR as a function of time (SSMBR)	6-5
<i>Figure 6.2</i> Relationship between SOUR and biomass parameters (up to 32 days of SSMBR operation)	6-7
<i>Figure 6.3</i> Relationship between SOUR and normalized biomass parameters	6-10
<i>Figure 6.4</i> Comparison of experimental and simulated SOUR profile: (a) simulation of model 1; (b) simulation of model 2.....	6-11
<i>Figure 7.1</i> Variation of $MLSS$ in bioreactor during the first 32 days of SSMBR operation	7-9
<i>Figure 7.2</i> Variation of SMP in bioreactor during first 32 days of the SSMBR operation	7-10
<i>Figure 7.3</i> Comparison of the experimentally measured TMP and the TMP calculated from mathematical model	7-11
<i>Figure 7.4</i> Simulated R_p for various initial porosities of membrane	7-12
<i>Figure 7.5</i> Simulated R_p with and without using the parameter n_p (for porosity 15%).	7-15
<i>Figure 7.6</i> Comparison of model simulation results with experimental results of SSMBR (a) $R_p + R_c$; (b) TMP	7-16
<i>Figure 7.7</i> Flowchart for the calculation of TMP	7-16
<i>Figure 7.8</i> Comparison of simulated TMP with experimental TMP of the CMBR.....	7-17
<i>Figure 7.9</i> Comparison of simulated TMP with experimental TMP of the CMBR (with modified value of exponent coefficient n_c of the model)	7-18

List of Notations and Abbreviations

A. List of notations

ΔP	Pressure gradient (transmembrane pressure)
μ	Permeate (or effluent) viscosity
μ_{20}	Permeate viscosity at 20 ⁰ C
μ_{aut}	Maximum growth rate of autotrophs
μ_{het}	Maximum growth rate of heterotrophs
μ_{SMP}	maximum growth rate of SMP
μ_T	Permeate viscosity at T ⁰ C
a	Threshold pore area
\AA	Angstrom
A_m (or A)	Membrane surface area
A_t	Total pore area
B	First-order endogenous decay rate coefficient
bE_i/bE_0	bEPS _i /bEPS ₀
b_H	Endogenous respiration rate
C	Sludge concentration
C_0	Inert COD in the influent
C_d	Coefficient of the lifting force of a sludge particle
C_m (or C_b)	Concentration of fouling particles
C_m^b	Concentration of particles entering the membrane pore
$\text{COD}_{c,\text{eff}}$	Colloidal COD in the effluent
COD_i	Total inert COD in the influent
COD_{perm}	COD in the permeate (effluent)
$\text{COD}_{s,\text{eff}}$	Soluble COD in the effluent
C_s	Inert COD in the effluent
C_{SMP}	Concentration of soluble particles entering the pores
$d_{f,o}$ (or $m_{d,o}$)	Membrane outer diameter
$d_{i,o}$ (or $m_{d,i}$)	Membrane inner diameter
d_p	Sludge particle diameter

D_s	Pore area fractal dimension
E_i/E_0	EPS_i/EPS_0
f	Membrane porosity
f_b	Fraction of biomass that ends up as microbial products
f_{bap}	Fraction of BAP produced during cell lysis
f_{BAP}	BAP fraction below critical molecular weight
f_{EPS}	growth associated EPS formation coefficient
$f_{EPS,d}$	non-growth associated EPS formation coefficient
f_s	fraction of suspended solids produced from EPS hydrolysis/dissolution
f_{UAP}	UAP fraction below critical molecular weight
G	Geometry factor for fluid flow through a pore
h_m	Membrane effective thickness
I	Fouling potential index
J	Flux (of flow)
J^*	Normalized flux
J_s^*	Normalized specific flux
J_{so}	Specific flux at time zero
J_t	Total flux
K	constant
K_1	UAP formation rate coefficient
K_2	BAP formation rate coefficient
K_{bap}	Half saturation coefficient for BAP
K_{eps}	EPS formation coefficient
$K_{h,bap}$	Hydrolysis rate of BAP
$K_{h,EPS}$	Rate of EPS hydrolysis/dissolution
k_{hyd}	First-order hydrolysis rate coefficient
$K_L a_{20}$	Oxygen transfer parameter
k_{MP}	Half saturation coefficient for microbial products
K_{SMP}	SMP half saturation coefficient for heterotrophs
k_a	An empirical parameter
L_0	Constant

L_b	Biofilm thickness
M_1/M_2	MLVSS/MLSS
$MLSS_{\text{sludge}}$	MLSS of sludge
M_{sc}	Mass of biomass accumulated on the membrane surface
N	Nitrogen
N_2O	Nitrous oxide
NaOCl	Sodium hypochlorite
n_c	Exponential coefficient for cake layer resistance
$NH_4\text{-N}$	Ammonia nitrogen
$NO_2\text{-N}$	Nitrite-N
$NO_3\text{-N}$	Nitrate- N
n_p	Exponential coefficient for pore fouling resistance
P	Phosphorus
PACl	Poly-aluminium chloride
$PO_4\text{-P}$	Phosphate P
Q	Flow rate
R^2	Squared value of correlation coefficient
R_{biofilm} (or R_b)	Resistance due to biofilm
r_c	Specific cake resistance
$R_c(z)$	Time-dependant cake layer resistance
R_{cake}	Resistance due to cake formation
R_m	Membrane intrinsic resistance
R_p	Pore fouling resistance
r_p	Specific resistance of pore fouling
r_p	Membrane pore radius
r_p	Pearson correlation coefficient
$R_p(z)$	Time-dependant pore blocking resistance
R_{sc}	Stable sludge film resistance
r_{sc}	Specific resistance of stable sludge film
R_{sf}	Dynamic sludge film resistance
r_{sf}	Specific resistance of dynamic sludge film

R_T	Total resistance
R_{Tot}	Total membrane resistance
S_{BAP}	BAP (COD units)
$sBOD_5$	Soluble 5-day biological oxygen demand
$sCOD$	Soluble COD
S_i	Influent substrate concentration
$SMP_{cake-mem}$	SMP concentrations in cake layer-membrane interface
$SMP_{permeate}$	SMP concentrations in the permeate
$SMP_{reactor}$	SMP concentration within the bioreactor
S_{ND}	Soluble biodegradable organic nitrogen
S_{NH}	Ammonia or ammonium nitrogen
SP_i/SP_0	SMP_i/SMP_0
S_{PO4}	Soluble phosphate
S_S	Readily biodegradable substrate
S_{UAP}	UAP (COD units)
t	Filtration period
t_f	Elapsed filtration time
u_b	Biofilm detachment rate during backwashing
$u_{f,a}$	EPS growth rate due to attachment
$u_{f,d}$	EPS growth rate due to detachment
U_{Lr}	Crossflow velocity of tap water
U_{sr}	Crossflow velocity of mixed liquor
V	Volume of permeate passed through the available membrane area
V_f	Water production within the filtration period of the operation cycle
V_f	Permeate volume after time t_f
V_s	Cumulative volume of permeate per membrane surface area
X	Biomass concentration
X_A	Active autotrophic biomass
X_{aut}	Autotrophic Biomass Concentration
X_{EPS}	EPS concentration
X_{GLY}	Stored glycogen in PAOs
X_{het}	Heterotrophic biomass concentration

X_{ND}	Particulate biodegradable organic nitrogen
X_P	Particulates from biomass decay
X_S	Slowly biodegradable substrate
Y_{BAP}	BAP formation constant
Y_{H2}	anoxic growth yield coefficient
Y_{MP}	Yield coefficient for growth on microbial products
z_c	Depth of cake layer
α	Stickiness of biomass particles
α_b	Specific resistance of biofilm
α_f	Membrane porosity reduction coefficient
α -factor	Oxygen transfer rate
α_{max}	An empirical parameter
α_o	An empirical parameter
α_p	An empirical parameter
α_v	Air scouring coefficient
β	Erosion rate coefficient of the dynamic sludge
β	Soluble Fouling Index (MFI) coefficient
γ	A coefficient for dynamic sludge compression
γ	Suspended solids MFI coefficient
$\gamma_{MP,A}$	Autotrophic microbial product formation constant
$\gamma_{MP,H}$	Heterotrophic microbial product formation constant
η	Viscosity of the permeate
η_f	Average fraction of soluble particles that accumulate in the pores
θ	Pore tortuosity
θ_f	Filtration period
v_{air}	Scouring air surface velocity
ρ_b	Biofilm density
ρ_c	Density of cake layer
ρ_p	Particle density

B. List of abbreviations

AOB	Ammonia-oxidizing bacteria
APHA	American public health association
ASMs	Activated sludge models
BAPs	Biomass associated products
BEPR	Biological excess phosphorus removal
bEPS	Bound extracellular polymeric substances
BF-MBR	Hybrid biofilm MBR
bio-P	Biological phosphorus
BNRS	Biological nutrient removal system
BOD	Biological oxygen demand
BPC	Biopolymeric clusters
C/N	Carbon to Nitrogen
C/P	Carbon to Phosphorus
CAS	Conventional activated sludge
CH	Carbohydrate
CIFI	Chemical-irreversible FI
CMBR	Conventional MBR
COD	Chemical oxygen demand
DOC	Dissolved organic carbon
DOM	Dissolved organic matter
EBPR	Enhanced biological phosphorus removal
ED	Electrodialysis
EMBRs	Extractive MBRs
EPS	Extracellular polymeric substances
F/M	Food to microorganisms ratio
FACASM1	Fully Coupled ASM1
FI	Fouling index
FS	Flat sheet
GAOs	Glycogen accumulating organisms
HF	Hollow fibre

HIFI	Hydraulic-irreversible FI
HRFI	Reversible FI by hydraulic backwash
HRT	Hydraulic retention time
IC	Inorganic carbon
IUPAC	International union of pure and applied chemistry (IUPAC)
IWA	International water association
LC-OCD	Liquid chromatography- organic carbon detection
MABRs	Membrane-aerated biofilm reactors
MBBR	Moving bed biofilm reactors
MBR	Membrane bioreactor
MF	Microfiltration
MFI _{0.45}	Modified fouling index
MFI _{MBR}	MFI of MBR
MFI _{sol}	MFI of soluble particles
MFI _{ss}	MFI of suspended particles
MLSS	Mixed liquor suspended solid
MLVSS	Mixed liquor volatile suspended solids
MT	Mutitube
NF	Nanofiltration
NFFB	Non-oven fabric filter bag
OHs	Ordinary heterotrophic organisms
OLR	Organic loading rate
OUR	Oxygen uptake rate
P	Phosphorus
PAC	Powdered activated carbon
PAOs	Phosphorus accumulating organisms
PFC	Polymeric ferric chloride
PHA	Polyhydroxyalkanoates
PN	Protein
poly-P	Polyphosphate
PS	Polysaccharide

PUS	Polyster-urethane sponge
PVDF	Polyvinylidene fluoride
R	Resistance
RBCOD	Readily biodegradable COD
RO	Reverse osmosis
SBNR	Shortcut biological nitrogen removal
sBOD ₅	Soluble 5-day biological oxygen demand
SCOD	Slowly biodegradable COD
SDI	Silt density index
SEM	Scanning electron micrographs
sEPS	Soluble EPS
SMBR	Submerged MBR
SMBR	Submerged membrane bioreactor
SMP	Soluble microbial products
SOUR	Specific oxygen uptake rate
SRT	Sludge retention time
SS	Suspended solids
SSMBR	Sponge submerged MBR
SSMBR	Sponge submerged MBR
T	Temperature
TC	Total carbon
TEP	Transparent exopolymeric particles
TFI	Total FI
TKN	Total kjeldahl nitrogen
TMP	Transmembrane pressure
TOC	Total organic carbon
TSS	Total suspended solids
TUDP	Technical university of Delf phosphorus
UAPs	Utilization associated products
UCT	University of Cape Town
UCTPHO	UCT phosphorus

List of abbreviations

UF	Ultrafiltration
UMFI	Unified FI
UTS	University of Technology Sydney
UV	Ultraviolet
VSS	Volatile suspended solids